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THE EFFECT OF LATERAL- AND LONGITUDINAL-RANGE CONTROL ON ALLOWABLE ENTRY CONDITIONS FOR A POINT RETURN FROM SPACE

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SUMMARY

The problem of return to a specified landing point on the earth from flight in space is considered by studying the interaction between an assumed control over the lateral and longitudinal range and the initial conditions of approach to the earth, given by orbital-plane inclination, vacuum perigee location, and time of arrival. The maneuvering capability in the atmosphere permits a point return for a range of entry conditions. A lateral-range capability of ±500 miles from the center line of an entry trajectory can allow a variation in the time of arrival of over 3-1/2 hours. Variation in the orbital-plane inclination angle can be as much as ±13°.

INTRODUCTION

It is probable that manned vehicles entering the atmosphere from space will perform aerodynamic maneuvers if they are to land at preselected sites. Imperfect control of the trajectory in space will result in deviations from the intended entry conditions. The atmospheric trajectory must then be modified by some form of aerodynamic maneuvering if the landing site is to be reached. It is the purpose of this report to show, for a given landing site, allowable tolerances in entry conditions resulting from modest aerodynamic control over the longitudinal and lateral range of the entry vehicle.

Five basic parameters define the entry condition: the inclination of the orbital plane with respect to the equatorial plane; the angular position of the vacuum perigee in the orbital plane; the absolute time of arrival; the velocity of the vehicle with respect to inertial space; and the angle of the flight path at entry with respect to the local horizontal. The tolerances on the last two parameters as a result of lifting, or maneuvering, capability have been considered in earlier papers (e.g., ref. 1) with respect to limiting the acceleration during entry and insuring capture of the vehicle in the atmosphere. These limitations are not considered further in the present paper. The velocity and the range of permissible entry angles come into the present paper only as they affect the attainable variations in range. The other three entry parameters are, however, specifically discussed to determine tolerances that permit a point return.

ANALYSIS AND DISCUSSION

Geometry and Simplifying Assumptions

The geometry used in this analysis is sketched in figure 1. This figure represents the northern half of the celestial sphere upon which is superimposed the plane of a return trajectory. In this case the celestial sphere is assumed to be the same size as the earth. It translates with the earth through space, but does not rotate with the earth. The polar axis and a line from the center of the earth toward the first point of Aries, the vernal equinox, define the plane of zero right ascension. The latitude of the landing site represents the locus of positions of the landing site on the celestial sphere during the course of a day. The position of the landing site can be defined by its latitude on the celestial sphere and the elapsed time since the landing site was in the plane of zero right ascension. (The landing site is, strictly speaking, in the plane of zero right ascension twice during the course of a day. Time, however, is measured from the intersection of the landing site with that portion of the plane in the direction of the first point of Aries.)

To simplify the analysis to follow, it was assumed that the earth does not rotate during the period of entry; although up to the time of entry, the earth does rotate and the landing site moves along its defining latitude on the celestial sphere. Since the time from entry to landing can range from 10 to 60 minutes, depending on the trajectory in the atmosphere, the earth actually rotates from 2.5° to 15° during the entry. Provision for a specific entry trajectory and the corresponding shift in the location of the landing site during the time spent in entry will modify the geometric parameters of the point return, but will not change any of the principal results of this analysis.

The geometry of this study is used deliberately to clarify the concept presented, although its use, rather than the use of a more classical astronomical notation, limits the location of the vacuum perigee to latitudes less than that of the landing site.

The analysis to follow is stated in terms of trajectories terminating in the northern hemisphere; consequently, an inclination angle of 90° defines a northerly heading of the flight path. A symmetrical set of solutions to those presented here exists for entry into the southern hemisphere toward a landing site at the equivalent south latitude. The existing figures can be used for this case if it is assumed that an inclination angle of 90° defines a southerly heading of the flight path.

Relation Between Inclination of the Orbital Plane and Incremental Longitude During Entry

On the basis of the geometry and assumptions described in the preceding section and the fact that the intersection of the orbital plane and the celestial sphere describes a great circle, it is possible to compute from the following equation

$$\Delta L = \frac{\pi}{2} - \sin^{-1}\left(\frac{\tan E}{\tan i}\right) \pm \left[-\frac{\pi}{2} + \sin^{-1}\left(\frac{\tan T}{\tan i}\right)\right]$$

the difference between the longitude of the vacuum perigee and the longitude at which the orbital plane intersects the latitude of the landing site. (See fig. 1 for notation.) This point of intersection represents the necessary position of the landing site in the absence of lateral maneuvers.

Relations between the orbital plane angle, i, and the incremental longitude, ΔL, are shown in figure 2 for landing sites along the 35° north latitude. Various latitude positions of the vacuum perigee are considered. These curves are plotted from the equation given above and are periodic in i about a mean of 90° with an amplitude determined by the landing site latitude and with a period of incremental longitude of 360°. As the latitude of the vacuum perigee shifts from the equator toward the latitude of the landing site, the curves progress from symmetrical to the sawtooth shape obtained when the two latitudes are equal.

The curves in this figure represent the conditions that must exist at the instant of entry if the trajectory plane is to intersect the landing site. Consider, for example, the condition at which the vacuum perigee is at 20° N. According to the figure, if the difference between the landing site longitude and the vacuum perigee longitude is to be zero (i.e., if both are on the same longitude) then the inclination of the orbital plane must be 90°, or perpendicular to the equator. For this example, the range measured over the earth's surface from vacuum perigee to landing would be from 20° N to 35° N latitude. If the inclination of the orbital plane is 40°, the landing site must be either 30° or 95° farther east of the vacuum perigee according to figure 2. This condition is similar to that illustrated in figure 1.

Effect of Lateral- and Longitudinal-Range Variations

Assumed vehicle range.- The envelope of possible landing sites for entry vehicles of low L/D (up to about 1/2) and common to all safe entry angles can be represented by a narrow rectangle superimposed on a line defined by the original direction of flight. This simplified shape is surprisingly accurate in representing the capabilities of such vehicles. As an example, for a large longitudinal range, most of the available lift is used to extend the longitudinal range, and only a small portion can be used to generate lateral acceleration. There is, because of the extended longitudinal range, a relatively long time available for the lateral range to build up. For a short longitudinal range, an increase in the available lateral acceleration is balanced by a proportionate decrease in the available time of flight. Control of the lateral range of up to ±500 miles from the center line can be considered typical for a vehicle with a lift-to-drag ratio of 1/2. The reason for assuming a simple geometric shape for the locus of possible landing sites is that it makes possible the straightforward calculation of the effect of lateral-range control to be discussed below.

Superposition of the range rectangle onto the entry trajectory.- If the assumed rectangular envelope of possible landing sites is superimposed on the track of the entry vehicle in its proper relation to the vacuum perigee, as is shown in figure 1, it is evident that for a landing at a specific point there is a certain amount of freedom in the position of the vacuum perigee, the absolute time of entry, and the orbital-plane inclination. The range of allowable positions of the vacuum perigee is especially large for the example shown in figure 1.

The allowable times of entry, for correct plane of entry and correct vacuum perigee position, are represented by the arc length of the target latitude covered by the range rectangle. Since this arc length is at least equal to the width of the rectangle, here taken to be 1000 miles, the entry-time tolerance for landing sites at 35° N latitude is a minimum of ±35 minutes and increases to much larger values as the orbital-plane inclination approaches the landing latitude. The tolerance permitted in the orbital-plane inclination is geometrically determined by the amount of rotation, Δi, that will keep the landing site within the range rectangle.

These considerations are made quantitative by computing the points of intersection of the landing-site latitude with the edges of the assumed range-capability rectangle at specific values of orbital-plane inclination. The results of these calculations are presented in figure 3. A separate sketch of the allowable combination of parameters has been made for each assumed value of vacuum perigee latitude. The center line of each sketch is taken from the appropriate curve of figure 2 and represents the allowable combination of parameters for a vehicle with no lateral-range capability.

The allowable combinations of parameters are indicated by the areas within the boundary lines. As an example, if the vacuum perigee of the entry trajectory is at the equator and the inclination of the orbital plane is 90°, the landing site can either lead or lag its nominal relative longitude of zero by almost 9°. This tolerance in relative longitude, as noted earlier, represents a tolerance in the time of entry of about 35 minutes either before or after the nominal time of entry. On the other hand, if the landing site and the vacuum perigee are on the same longitude, $\Delta L = 0$, the orbital-plane inclination can be as much as 13° either east or west of the nominal heading of due North.

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As the orbital-plane inclination is reduced toward the value of the target latitude, the tolerance in incremental longitude reaches a maximum of $\pm 54^\circ$. This is equivalent to an allowable variation in time of entry of about 3-1/2 hours, either leading or lagging the nominal time of entry.

It should be borne in mind that control of the orbital-plane inclination remains perhaps the most powerful method by which return to a preselected landing site can be achieved. For example, suppose that in figure 1 the landing site lies just outside the range rectangle. A slight tilting of the orbital plane, accomplished during midcourse flight, brings the target back into the attainable range. This is the significance, in figure 3, of changing the variable i.

Although not presented here, calculations show that the computed change in the incremental longitude due to changes in width of the range rectangle is, for these small values, almost a linear function of the lateral-range control capability. A lateral-range variation of ±250 miles, for instance, can produce a change in the incremental longitude very close to half that produced by a lateral-range variation of ±500 miles.

Longitudinal-range limitations.- The limits of control of the longitudinal range are assumed to be a minimum of 2000 miles from point of entry and maximums of 5000 and 7500 miles. These values are representative of those attainable by a vehicle with a lift-drag ratio of 1/2 approaching the earth at escape velocity. The point of entry was assumed to be 10° of arc ahead of the vacuum perigee. This displacement will vary with the entry angle (for normal return trajectories the displacement is very nearly equal to twice the entry angle), but for the present simple generalization, the constant value was used.

Again in figure 1, it can be seen that there will be, for example, a maximum value of relative longitude between the vacuum perigee and the landing site because of the maximum longitudinal boundary of the range rectangle.

The restrictions imposed on the landing site location because of these assumed longitudinal-range limitations have been computed and are shown in figure 3 as hatched boundaries, identified by the corresponding values of longitudinal range.

For vacuum perigee locations close to the equator, the limitation on minimum range is not important since even the closest position of the landing site at the assumed latitude of 35° N is within the capability of the vehicle. Thus, the 2000-mile minimum does not appear on figures 3(a) or (b). For vacuum perigee latitudes closer to the landing-site latitude, the assumed limitation of minimum range blocks out areas of otherwise possible entries that have inclination angles close to 90°. Such polar trajectories may be desirable as a means of minimizing exposure in the Van Allen belt radiation while on a return trajectory. The effects of the maximum longitudinal-range limitation of the vehicle are apparent in the figures.

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CONCLUSIONS

Lateral-range control of ±500 miles for a vehicle entering the atmosphere from space has been shown to allow significant variations in the return orbit while still permitting a landing at a preselected point along the 35° N latitude. The allowable variations in the orbital-plane inclination angle can be as much as ±13° for craft capable of moderate maneuvers in the atmosphere. The variation in the nominal rotational position of the earth at the instant of entry can be as great as ±54°, equivalent to a variation of ±3-1/2 hours from the nominal time of entry into the atmosphere.

Ames Research Center
National Aeronautics and Space Administration
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REFERENCE

1. Chapman, Dean R.: An Analysis of the Corridor and Guidance Requirements for Supercircular Entry into Planetary Atmospheres. NASA TR R-55, 1959.

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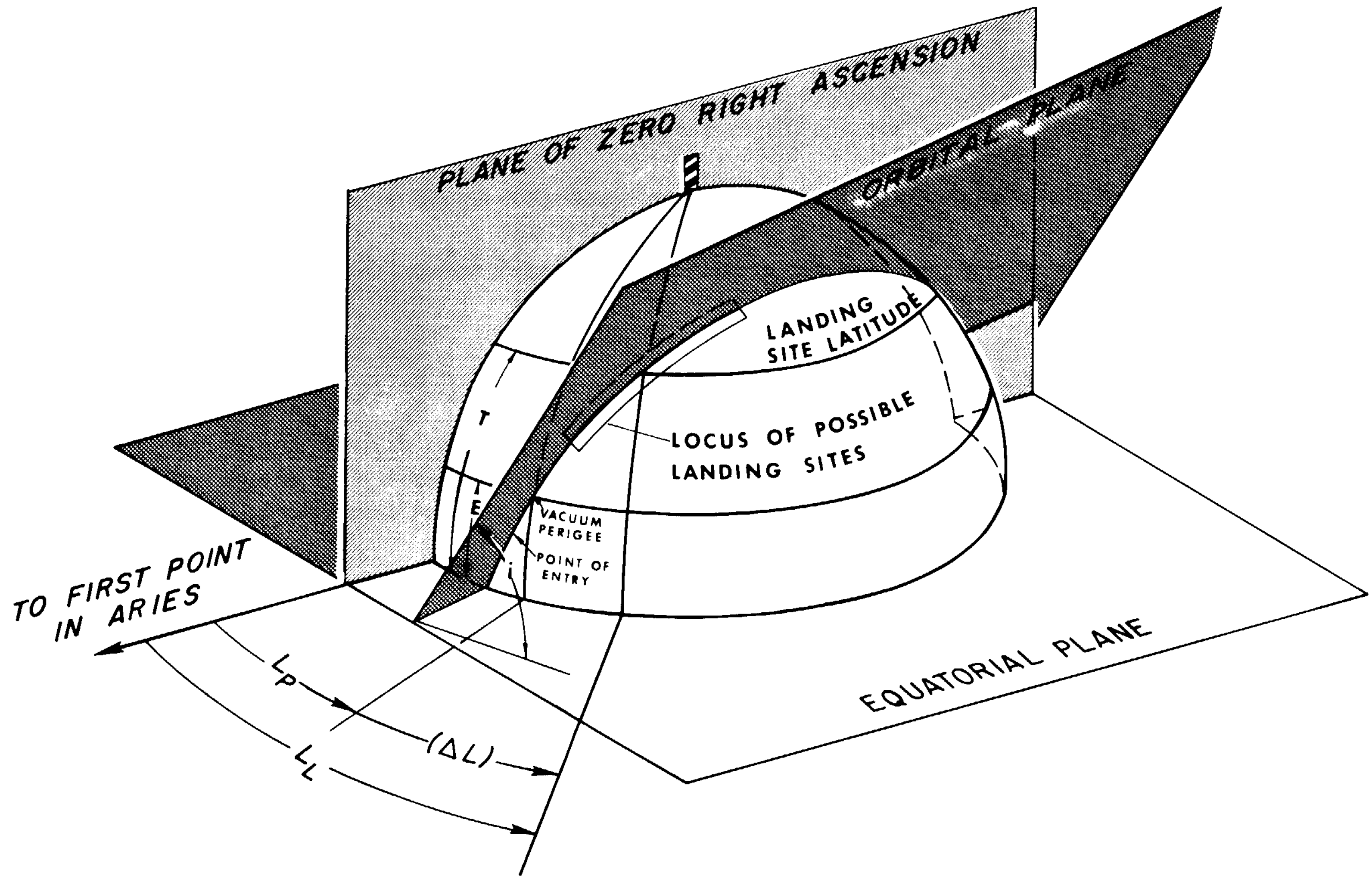

Figure 1.- Geometry of entry.

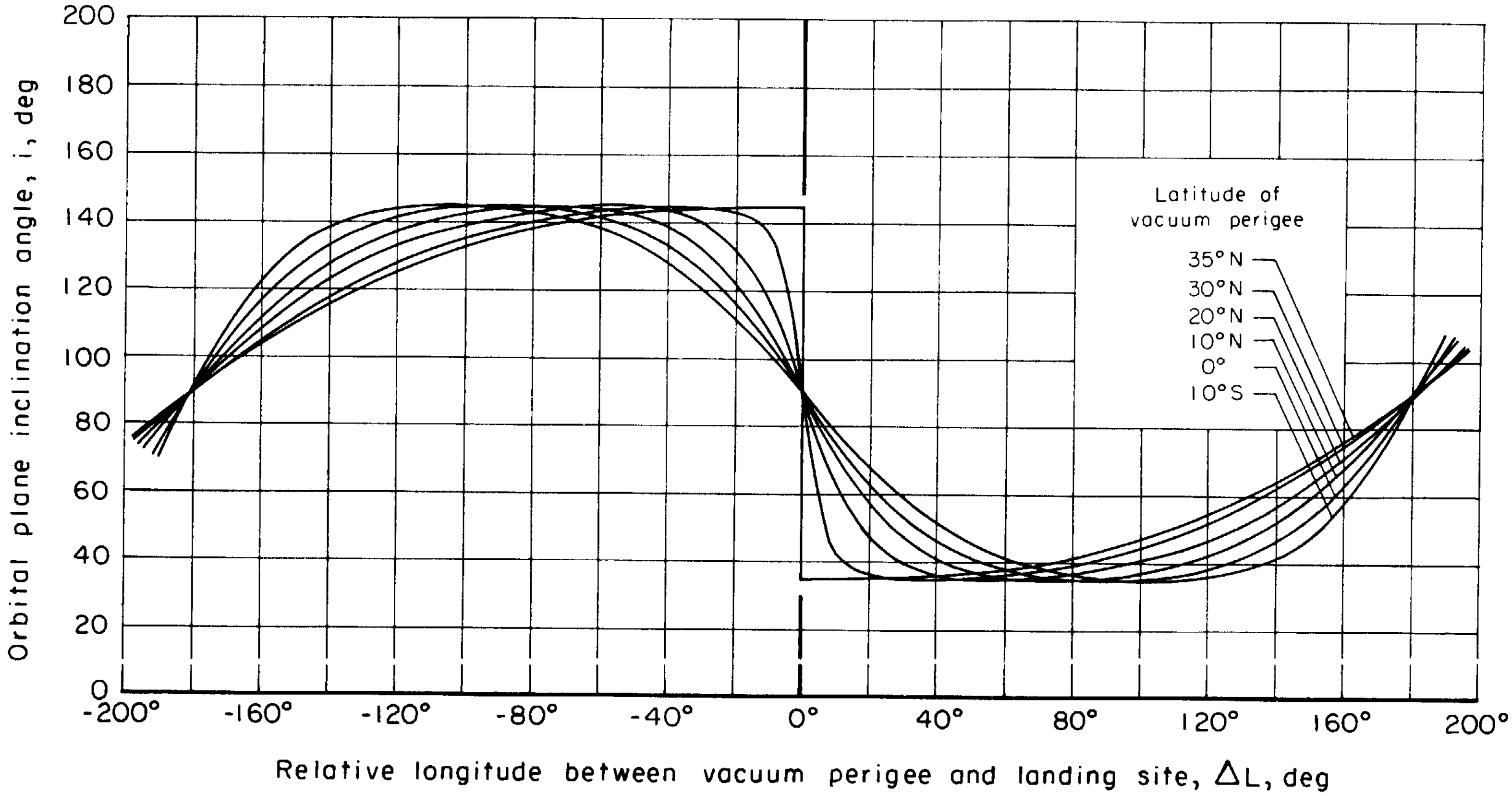

Figure 2.- Trajectory conditions necessary at entry for point return at 35° N latitude; no lateral-range capability.

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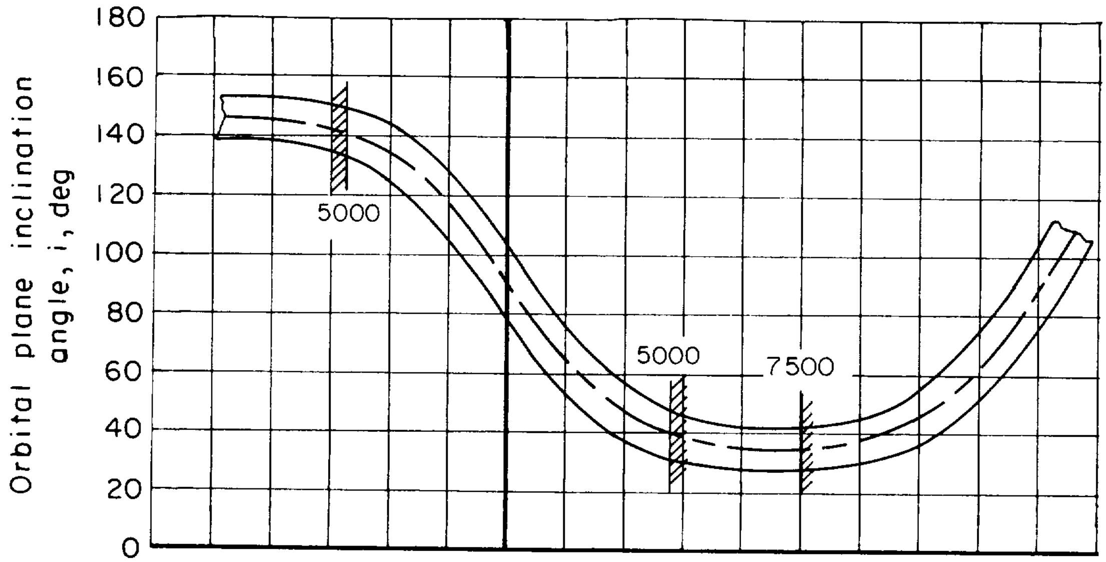
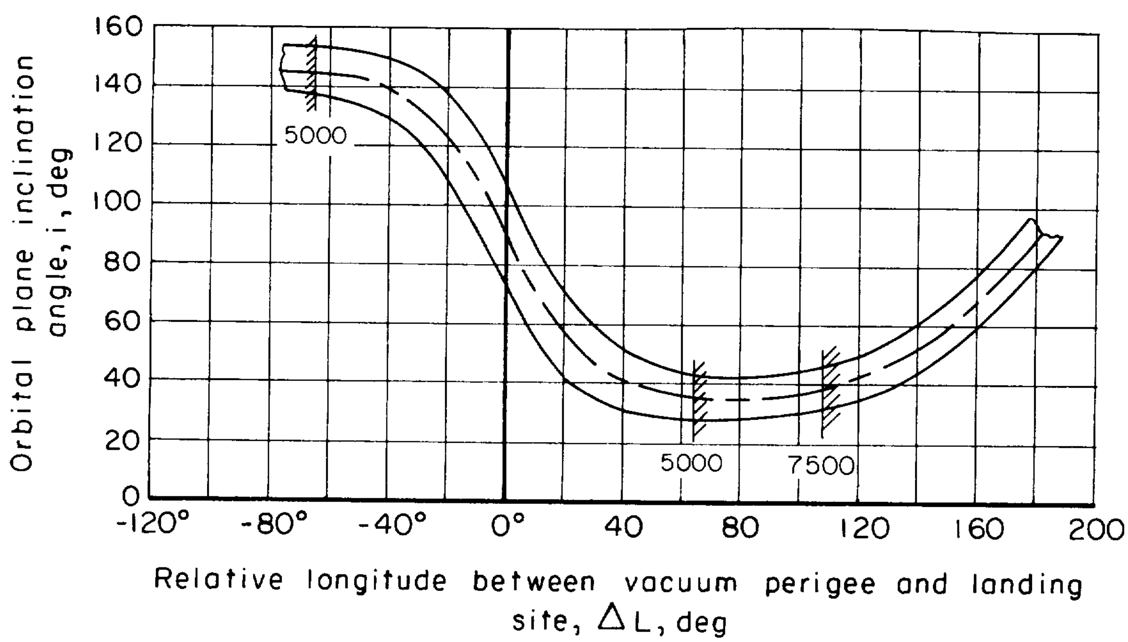
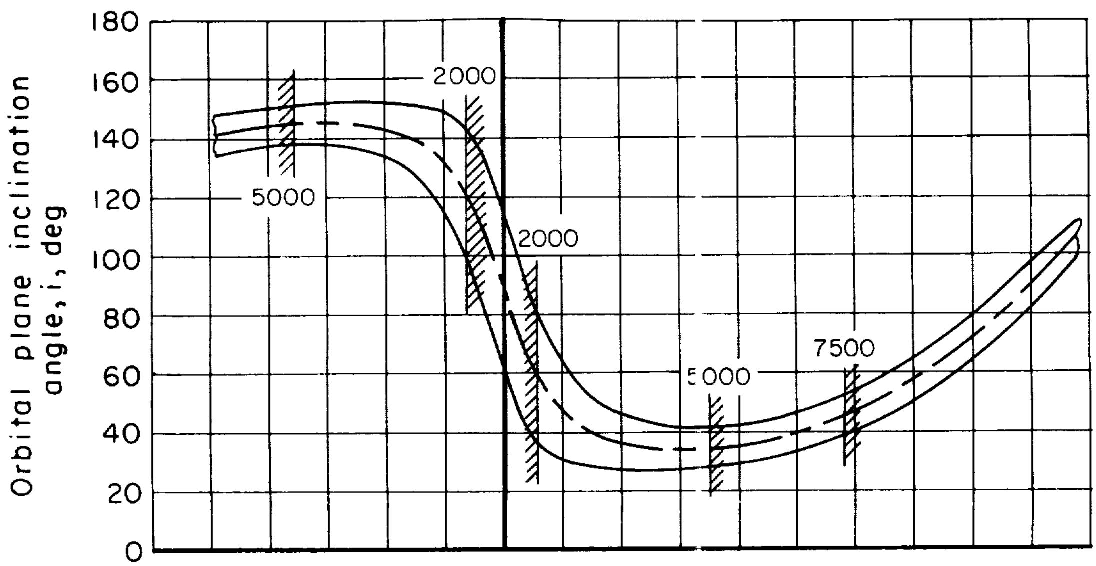


(a) Vacuum perigee at 0° latitude.

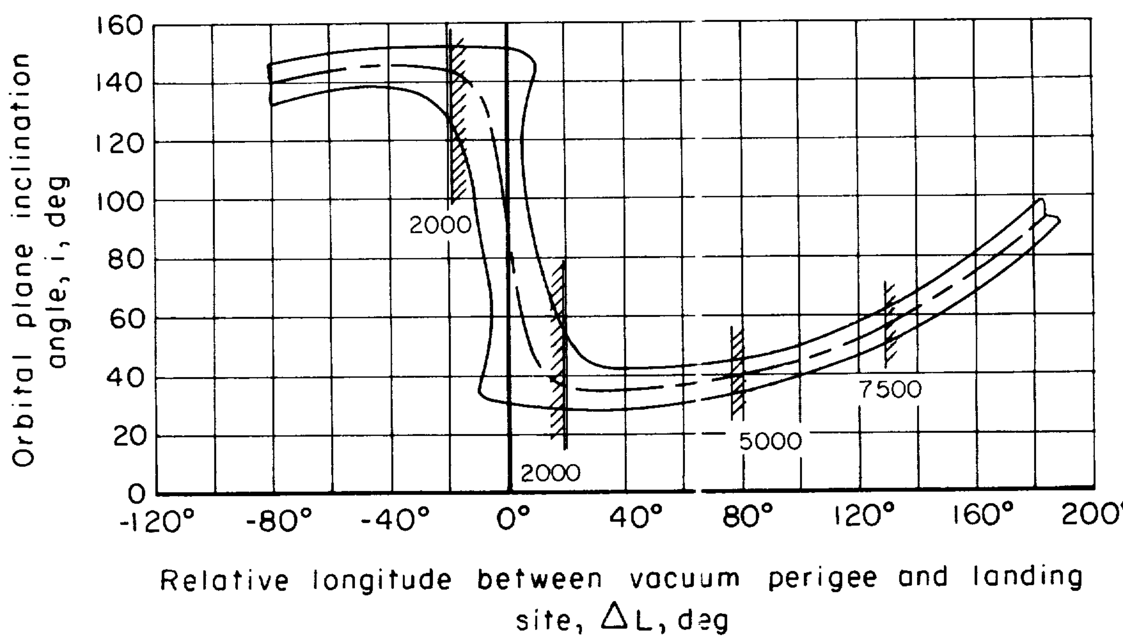


(b) Vacuum perigee at 10° N latitude.

Figure 3.- Trajectory conditions necessary at entry for point return at 35° N latitude; lateral range controllability of ±500 miles; longitudinal range as shown on hatched boundaries.



(c) Vacuum perigee at 20° N latitude.



(d) Vacuum perigee at 30° N latitude.

Figure 3.- Concluded.

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